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Assessment of optimal passive suspensions regarding motion sickness mitigation in different road profiles and sitting conditions

Georgios Papaioannou[1], Jenny Jerrelind[1], Lars Drugge[1] and Barys Shyrokau [2]

Abstract— **Automated vehicles (AVs) are expected to lead the evolution of mobility. Motion sickness, known as car sickness, is one of the main issues AVs will face, and could jeopardise their wide impact. However, a limited work has been done on how the optimisation of suspension dynamics could contribute. In this direction, this paper explores the mitigation of car sickness and the improvement of ride comfort through the optimisation of passive suspension systems. More specifically, a half car model, which represents a passenger vehicle from IPG/CarMaker, is used to optimise front suspension system for minimising comfort, but also maintaining vehicle handling while the vehicle is driving over two different road classes. The evaluation of comfort is conducted using the common standardised metric suggested by ISO-2631. After having obtained the optimum design solutions, the optimal solutions are simulated using IPG/CarMaker by assigning the road profiles on a 23 km long countryside road path. Then, vehicle accelerations are transferred to the occupant's head using appropriate models from the literature for both back-on and back-off sitting conditions. Afterwards, car sickness and ride comfort are further assessed to explore in detail how the tuning of the suspension systems through optimisation has minimised the first and enhanced the latter. For the assessment of car sickness, a three dimensional detailed biomechanical human model is used. The results imply that the pitch velocity seems more suitable, as a cost function for optimising the suspension systems with regards to motion sickness mitigation. Therefore, it should be considered either on its own or in combination with metric suggested by ISO-2631.**

I. INTRODUCTION

AVs are expected to constitute almost 60% of vehicle sales, and 40% of all vehicle travel by 2050 [1]. At the same time, there are still important challenges able to jeopardise the AVs wide impact. Consumers consider the ability to engage in other leisure activities or be more productive while being driven, among the three most important reasons for adopting AVs [2]. However, the majority of the envisaged designs of fully automated vehicles, such as when the vehicle control is handed over, occupants are seated backwards or their view to the road ahead is blocked by displays or internal structures, increase significantly the incidence of motion sickness (MS) [3]. So, a refocus on MS and comfort is crucial in order to secure the AVs wide impact and their acceptance by the society.

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Motion sickness is commonly described as a variable range of responses to the stimulus of actual or perceived motion, and is considered as the human's natural response to unnatural movements. There are multiple explanations why motion sickness occurs. The evolutionary theory [4] attributes motion sickness to the continuous misalignment between the different sensory inputs (visual, vestibular and proprioceptive). On the other hand, according to the sensory conflict theory [5], motion sickness is caused by the mismatch between sensed and anticipated (based on prior experience) sensory inputs. The posture instability theory [6] attributes motion sickness to prolonged uncoordinated configuration of the body and its segments, rather than sensory stimulation.

Car sickness is MS that results from provocative motion frequencies occurring in a road vehicle in transit. On contrary to the past when the main issues were cause, function, symptoms, and estimation, nowadays the researchers focus on how it can be minimised. Even though vehicle dynamic factors can affect car sickness likelihood, the literature only recently started focusing on them from the perspective of motion planning [7]. Motion planning is a proven countermeasure of MS incidence as it could reduce excessive head and body motion, and should be considered. However, the excessive reduction of the speed that the motion planner might suggest, could dissatisfy users as journey time might increase, affecting the user acceptance and satisfaction. Therefore, additional approaches of enhancing motion comfort should be considered without affecting journey time to a great extent or even allowing the vehicle to keep it short.

This paper explores the mitigation of car sickness and the improvement of comfort through the optimisation of passive suspension systems, a subject that hasn't been studied so far to the authors knowledge. More specifically, in this work, a half car model, which represent a passenger vehicle, is used to optimise its suspension system for minimising comfort, but also maintaining vehicle handling while the vehicle is driving over class B and C road profiles. The evaluation of comfort is conducted with the common standardised metric suggested by ISO-2631 for suspension optimisation following works in the literature [8]. The optimal solutions obtained are simulated using IPG/CarMaker, where the road profile, for which the suspensions are optimised, is assigned to a 23 km long countryside road path. Then, the vehicle accelerations are transferred to the occupant's head for both back-on and back-off sitting positions using appropriate transmissibility functions that exist in the literature. Afterwards, the optimum suspension designs are further assessed using a multi-dimensional biomechanical human and motion sickness model. In this way, a detailed exploration is performed regarding how the tuning of the suspension system through optimisation have mitigated MS and enhanced comfort. At the same time, the assessment for the two sitting conditions provides insights with how the occupants will react in case they are involved in non-driving activities that made them to not support their back to the seat.

II. Methodology

A. Vehicle modeling

The half car model, shown in Figure 1, is selected for optimising the suspension systems, as it is the most efficient [9]. The model includes the front and rear axles of the vehicle allowing both pitch and bounce phenomena to be observed, but lateral motions are not considered. The vehicle body is considered as a rigid body of mass, m_s, which is equal to half of the total mass of the vehicle. The suspensions consist of linear springs (K_F, K_R) and passive dampers (C_F, C_R). The front and rear tyres are modelled as linear springs (K_{TF} and K_{TR}), which receive as input the irregularities of the road profile. The distance of the front and rear unsprung masses (m_F and m_R) from the center of mass are equal to a_F and a_R, respectively. The parameters for the half car model, which have been extracted from the validated vehicle model of a passenger car, are shown in Table I.

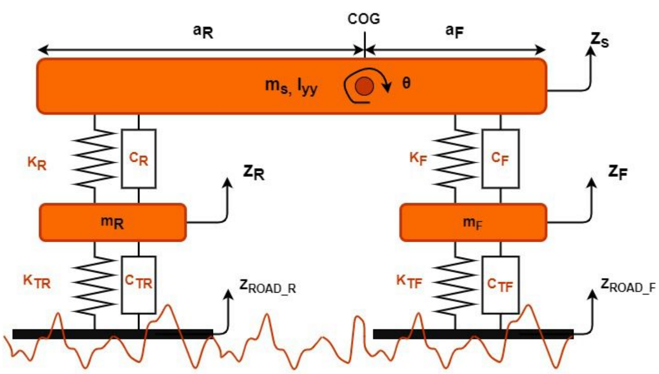


Fig. 1: Half car model.

TABLE I: Parameters of half car model

Parameter	Value	Parameter	Value
m_s[kg]	544.5	a_F[m]	1.02
I_{yy}[kg m^2]	1346	a_R[m]	1.64
m_F[kg]	45.24	K_{TF}[N/m]	4.50 10^5
m_R[kg]	35.06	K_{TR}[N/m]	4.50 10^5
C_R[Nm/s]	3000	K_R [m]	3.00 10^4

The governing equations of the vehicle model are the following:

$$
\begin{aligned}
m_s\ddot{z}_s + C_F\dot{ST}_F + C_R\dot{ST}_R \\
+ K_F ST_F + K_R ST_R = 0
\end{aligned}
\tag{1}
$$

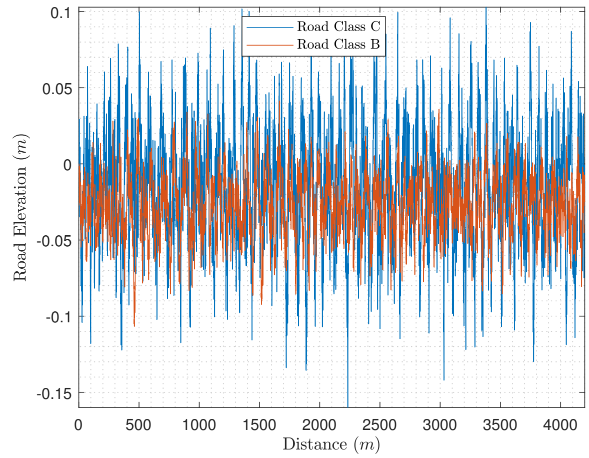


Fig. 2: Random road profiles (z_{ROAD}) of Class B and C roughness designed according to ISO-8608 [10].

$$
\begin{aligned}
I_{yy}\ddot{\theta} - a_F C_F\dot{ST}_F + a_R C_R\dot{ST}_R \\
- a_F K_F ST_F + a_R K_R ST_R = 0
\end{aligned}
\tag{2}
$$

$$
\begin{aligned}
m_F\ddot{z}_F - K_F ST_F - C_F\dot{ST}_F \\
+ K_{T_F}(z_F - z_{ROAD_F}) = 0
\end{aligned}
\tag{3}
$$

$$
\begin{aligned}
m_R\ddot{z}_R - K_R ST_R - C_R\dot{ST}_R \\
+ K_{T_R}(z_R - z_{ROAD_R}) = 0
\end{aligned}
\tag{4}
$$

where ST_F (= $z_s - z_F - a_F\theta$) and ST_R (=$z_s - z_F + a_R\theta$) are the front and rear suspension travel; z_{ROAD_F}, z_{ROAD_R} the excitations applied to the vehicle model, which are considered as random road profiles of Class B and C (see Figure 2). The rear wheels excited by the same road profile as the front wheels, but with a time delay $t_{distance}$=($\frac{a_F+a_R}{V}$), which is due to the vehicle wheelbase (a_F + a_R).

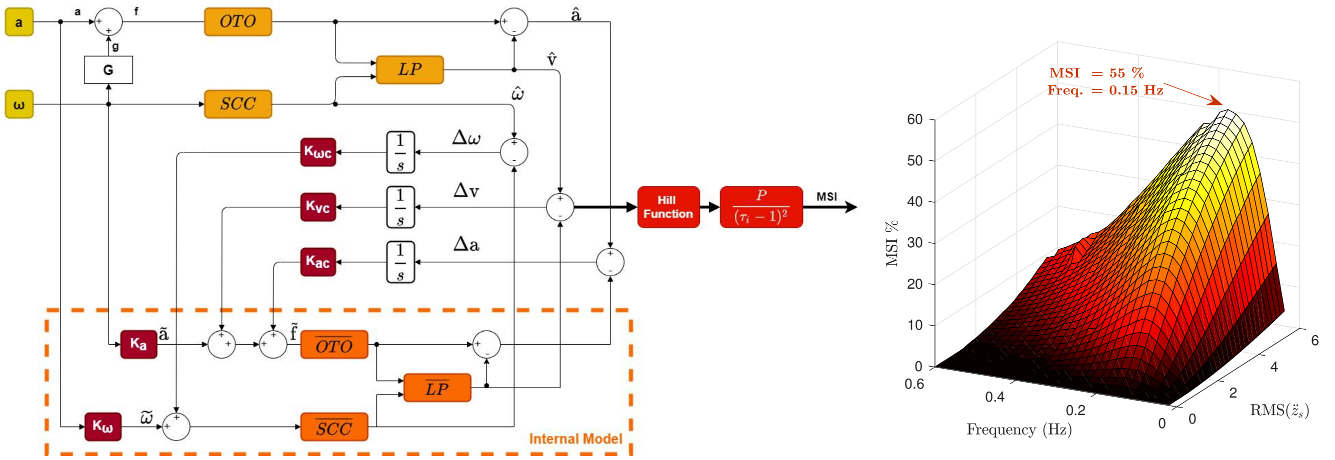
B. Motion comfort

In this work, standardised metrics suggested by ISO-2631 [13] are used during the optimisation to assess comfort, while a multi-dimensional model is used to assess MS with the measurements obtained from the simulation of the vehicle's digital twin in enhanced simulation software IPG/CarMaker.

1) ISO-2631: ISO-2631 standard provides a guideline for measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock. According to it, the ride comfort is assessed by combining the root mean square (RMS) values of the weighted accelerations (RC_{W_i}) measured at the vehicle's centre of gravity. The weighted RMS value can be calculated as:

$$
RC_i = \left(\frac{1}{t}\int_0^t a_{i_W}^2 d\tau\right)^{\frac{1}{2}}
\tag{5}
$$

where a_{i_W} stands for the weighted accelerations at the i^{th} direction, with appropriate filters (W_i) being applied on it for the vertical [13] and the lateral [14] vibrations.



(a)

(b)

Fig. 3: (a) Six degrees of freedom subjective vertical conflict model, and (b) its validation with regards from Bos et al. [11] and McCauley et al. [12].

2) Motion sickness assessment model: Motion sickness is commonly described as a variable range of responses to the stimulus of actual or perceived motion, and is considered as the human's natural response to unnatural movements. The main cause is considered the mismatch between sensory information from the vestibular system and the estimated sensory information from internal model. As an extension of a one-dimensional model [11], who modeled the sensory inputs processed by the vestibular system in the vertical direction, a three dimensional nervous system model [15] considered that the vertical conflict occurs by rotation stimulus. The model is illustrated in Figure 3a. In summary, the part which is framed by dots is the internal model that predicts the human motion; G describes the human body rotation and the direction of gravity is seen from the head; SCC and SCC$_B$ are the semicircular canals and their internal model, respectively; LP and LP$_B$ are estimating the sensed and internal dynamics, respectively; OTO is the otolith organ, but here it is assumed as a unit matrix; K_a and K_ω are gains to estimate accurately the occupant's head translational accelerations and rotational velocities, while K_{a_c}, K_{ω_c} and K_{v_c} are feedback gains. The inputs to assess MS with the MS model are a_{x_h}, a_{y_h}, a_{z_h}, $\dot{r}_h$, $\dot{\phi}_h$ and $\dot{\theta}_h$, where a_{x_h}, a_{y_h}, a_{z_h} are the longitudinal, lateral and vertical translational accelerations and $\dot{r}_h$, $\dot{\phi}_h$ and $\dot{\theta}_h$ are the yaw, roll and pitch rotational velocities at the head reference frame. This model is validated with regards to the results by Bos et al. [11] and McCauley et al. [12], which is shown in Figure 3b.

3) Transmissibility models: In this work, the three dimensional model is used to assess car sickness. However, the inputs of the motion sickness incidence (MSI) model are in the head reference frame, therefore the accelerations (a_x, a_y, a_z, $\ddot{r}$, $\ddot{\phi}$ and $\ddot{\theta}$) from the vehicle CoG have to be transmitted from the chassis to the head (a_{x_h}, a_{y_h}, a_{z_h}, $\ddot{r}_h$, $\ddot{\phi}_h$ and $\ddot{\theta}_h$). In this direction, seat-to-head transmissibilities from experimental tests and simulation models are used. More specifically, the vehicle vertical accelerations are transferred to the head, according to Equation 6, using the transfer functions (T_z) obtained from the human body model presented in Figure 4.

$$a_{z_{h_0}} = T_z \ddot{a}_z \tag{6}$$

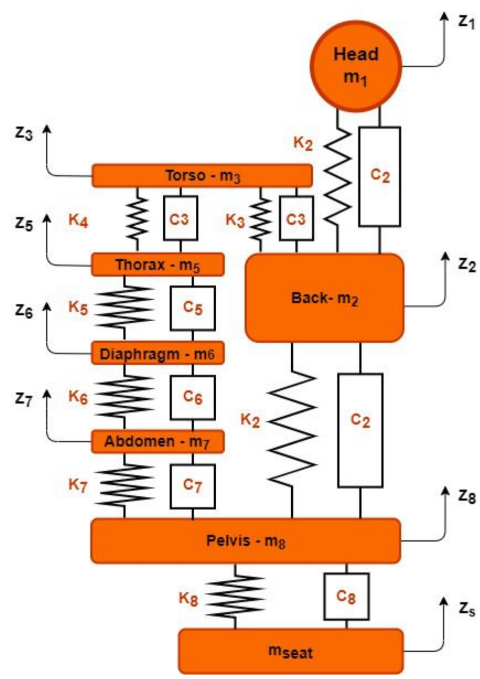


Fig. 4: The biomechanical human body model [16].

where $a_{z_{h_0}}$ is the head vertical acceleration without the effect of any other excitation. Also, a_x and a_y are assumed to be transmitted to the head as:

$$a_{x_{h_0}} = \ddot{a}_x, \quad a_{y_{h_0}} = \ddot{a}_y \tag{7}$$

where $a_{x_{h_0}}$ and $a_{y_{h_0}}$ are the longitudinal and lateral head accelerations without the effect of any other excitation.

Regarding yaw accelerations ($\ddot{r}$), Paddan et al. [17] assessed their transmission from the seat to the head (T_{yaw}), both at back-on and back-off sitting conditions, i.e. when the occupant lies to the backrest or not. These transfer functions are used in this work according to Equation 8:

$$\ddot{r}_h = T_{yaw}\ddot{r} \tag{8}$$

where $\ddot{r}_{h_0}$ is the yaw head acceleration without the effect of any other excitation. Also, Paddan et al. [18] evaluated experimentally not only how roll ($\ddot{\phi}$) and pitch ($\ddot{\theta}$) accelerations are transmitted to the head from the seat, but also how these accelerations affect the rest translational and rotational accelerations both at back-on and back-off conditions. Regarding the pitch accelerations ($\ddot{\theta}$), they assessed the transmissibility (T_θ) of $\ddot{\theta}$ to $\ddot{\theta}_h$, but also their effect (T_{θ_x} and T_{θ_z}) to a_{x_h} and a_{z_h}. These transmissiblities are used in this work according to Equation 9. Similarly for the roll accelerations ($\ddot{\phi}$), they [18] assessed their transmissibility (T_ϕ) to the head ($\ddot{\phi}_h$), but also their effect (T_{ϕ_y} and T_{ϕ_r}) to a_{y_h} and $\ddot{r}_h$. These are used in this work according to Equations 10.

$$a_{x_h} = T_{\theta_x} a_{x_{h_0}}, \quad a_{z_h} = T_{\theta_z} a_{z_{h_0}}, \quad \ddot{\theta}_h = T_\theta \ddot{\theta} \tag{9}$$

$$a_{y_h} = T_{\phi_y} a_{y_{h_0}}, \quad \ddot{r}_h = T_{\phi_r} \ddot{r}_{h_0}, \quad \ddot{\phi}_h = T_\phi \ddot{\phi} \tag{10}$$

III. OPTIMISATION

As mentioned before, this paper explores the mitigation of car sickness and the improvement of comfort through the optimisation of passive suspension system. In this direction, an optimisation problem is configured, using the half car model, aiming to minimise comfort and maintain vehicle handling by optimising its front suspension.

A. Configuration

A multi-objective optimisation problem is formulated where the following objective functions are considered to represent the objectives of car sickness and handling:

$$F_1 = RC_z \tag{11}$$

$$F_2 = RMS(z_F - z_{RoadF}) + RMS(z_R - z_{RoadR}) \tag{12}$$

where F_1 considers the standardised metric suggested by ISO-2631, and F_2 is the sum of the root mean square of the front and rear tyre deflections, which are related with the road holding performance to improve vehicle handling. Regarding the design variables, only the front suspension parameters are considered (K_F and C_F) in an attempt to extract more safer conclusions regarding the potential effect of suspension to MS mitigation. As upper and lower bounds for the design variables, $[15000 : 60000]$ and $[500 : 3000]$ are selected for K_F and C_F, respectively. The optimisation is conducted for two different cases, where Class B and C roads (Figure 2) are used as excitations. The optimisation is conducted using the GAMULTIOBJ toolbox from MATLAB 2017b.

B. Results

The optimisation results are presented in a three dimensional plot (Figure 5), showing the relation of the optimal design variables with the discomfort levels provoked to the occupants. According to Figure 5, the optimal damping coefficient (C_F) has converged to values across the whole range of bounds, while the spring stiffness (K_F) has converged to values closer to the lower bound providing solutions where K_F is lower than K_R (= 30000 N/m). Regarding the car sickness levels, the stiffening of both the damper and the spring leads to higher discomfort as expected, but the stability is increased.

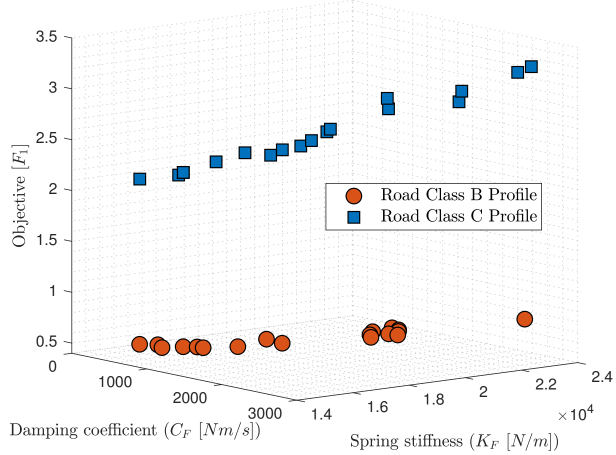


Fig. 5: The optimal design variables (K_F and C_F) with regards to the comfort levels (F_1-Objective).

IV. FURTHER CAR SICKNESS ASSESSMENT

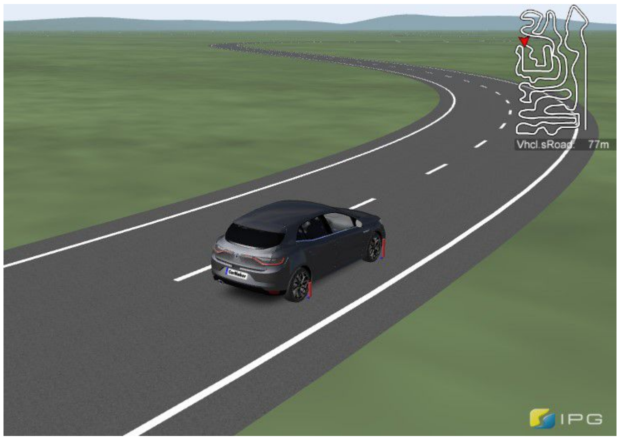
A. Enhanced multi-body simulation

While the optimisation is conducted for the ride vehicle model, the IPG/CarMaker based simulations (Figure 6b) consider also an intense path to provoke more the car sickness incidence. Hence, the two road profiles are assigned to a 23 km road path (Figure 6b), which at the end includes a 1.5 km straight line for the occupant's MS to habituate. This road path is artificial, however the levels of accelerations induced are comparable with a real-world country road. In order to focus on the suspensions impact on MS, the artificial driver model (AI driver) from IPG/CarMaker is used to always follow the centreline of the road path and maintain constant velocity.

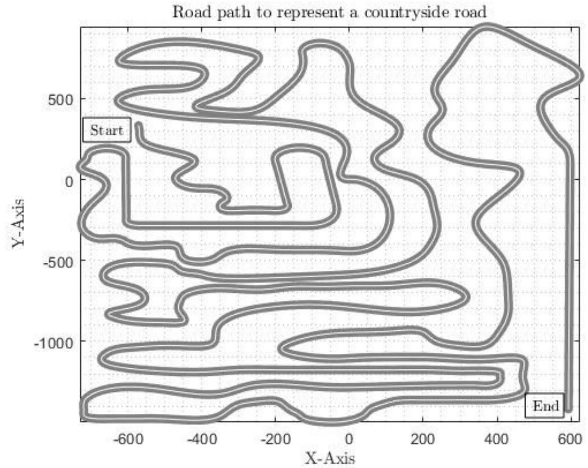
B. Results

After obtaining the optimisation results, the following procedure is considered for the car sickness assessment:

1) The commercial software is used to simulate the optimum suspension design variables and extract the a_x, a_y, a_z, $\ddot{r}$, $\ddot{\theta}$ and $\ddot{\phi}$ vehicle responses for each case. The simulations are conducted for the two cases, where the different road roughness profiles (Class B and C) are applied to the road path.



(a)



(b)

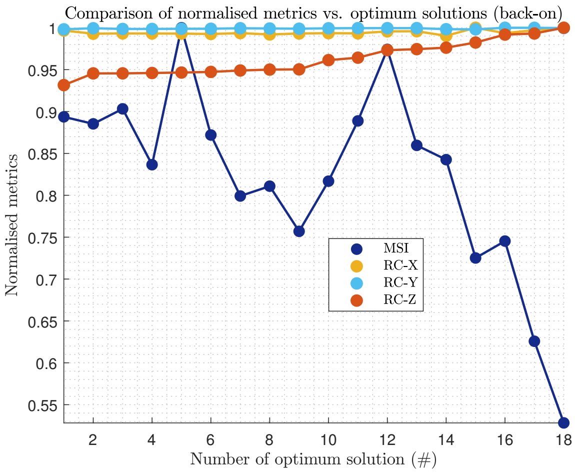
Fig. 6: (a) Vehicle used in IPG/CarMaker and (b) X and Y co-ordinates for the road path..

2) The transmissibility models are applied, as described in Equations 6-10, to transfer the vehicle responses to the occupant's head (a_{x_h}, a_{y_h}, a_{z_h}, $\ddot{r}_h$, $\ddot{\phi}_h$ and $\ddot{\theta}_h$). The $\ddot{r}_h$, $\ddot{\theta}_h$ and $\ddot{\phi}_h$ are integrated to obtain their corresponding velocities ($\dot{r}_h$, $\dot{\theta}_h$ and $\dot{\phi}_h$) to be used as inputs to the MSI model alongside a_{x_h}, a_{y_h} and a_{z_h}. The transmissibility models of two sitting conditions are used in this work. This is to investigate how the occupants will react in case they are involved in non-driving activities that made them not support their back to the seat.
3) For the in-depth assessment of the optimal suspension design, various metrics are evaluated. More specifically, the maximum level that the MS accumulated (MSI metric) is calculated via the MS model. Then, the RCZ (Equation 5) is re-calculated using the commercial software measurements, while the root mean square values of the rotational velocities ($\dot{r}_h$, $\dot{\theta}_h$ and $\dot{\phi}_h$) are calculated respectively (RCr, RCP and RCR). Similarly, the root mean square values of the translation accelerations (a_{x_h} and a_{y_h}) are calculated (RCX and RCY).
4) The above metrics are normalised with their maximum values among the optimum design solution and are plotted in Figures 7 and 8 for the road class B and C case, respectively. More specifically, in Figures 7a, 7c, 8a and 8c, the normalised MSI metric is plotted in comparison with the normalised RCZ, RCX and RCY for two sitting conditions. In Figures 7b, 7d, 8b and 8d the same metric is plotted in comparison with the normalised RCP and RCr. The normalisation with their maximum value allows to not focus only on their values, but (a) also on the metrics behaviour, (b) possible correlation and (c) the assessment of the optimum solutions with regards to MS mitigation and comfort enhancement.

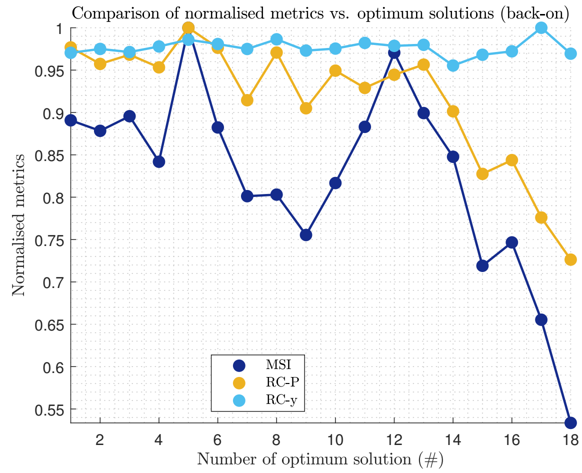
Using the artificial driver model of IPG/CarMaker, the lateral accelerations and yaw velocities are mostly kept similar in all the cases, as shown in Figures 7 and 8, where RCY and RCr have insignificant variations. Only the RCr in the road class C case (Figure 8) isn't maintained constant or with insignificant variations, as the intense road profile forced the driver model in few adjustments in the requirements. Also, based on Figures 7a, 7c, Figures 8a and 8c, where the translational accelerations are compared with the MSI metric, the optimal solutions have increasing RCZ values, as indicated by the optimisation (Figure 5). However, in both the road class cases and the two sitting conditions, the increasing behaviour in the RCZ metric is not also present in the MSI, which questions the suitability of the car sickness objective (F_1) during the optimisation. On the other hand, according to Figures 7b, 7d, 8b and 8d, the MSI metric is following the same increasing-decreasing pattern with the RCP, which is the root mean square of the pitch velocity. The above outcome is more obvious in the back-off sitting positions, where RCP and MSI illustrate similar levels of increase and decrease as well and not only similar pattern. This validates the already discussed sensitivity of human to pitch motion compared rather than lateral or vertical vibrations [19].

V. Conclusions

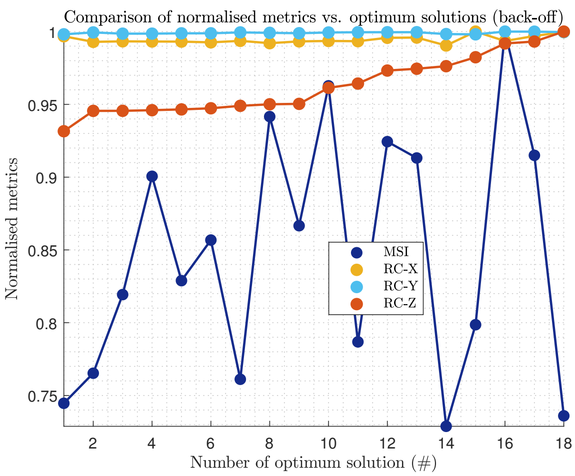
This paper explored the mitigation of car sickness and the improvement of comfort through the optimisation of passive suspension system. In overall, the pitch vibration levels seemed to be in greater alignment with regards to the motion sickness metrics, on contrary with the standardised metric suggested by ISO-2631. More specifically, the increase (decreases) in the metrics related with the latter are not leading to an increase (decrease) in the motion sickness metric. At the same time, the motion sickness metric is following the change in the pitch vibrations levels. The above remark implies a potential unsuitability of the metric suggested by ISO-2631, i.e. the weighted vertical accelerations, as a cost



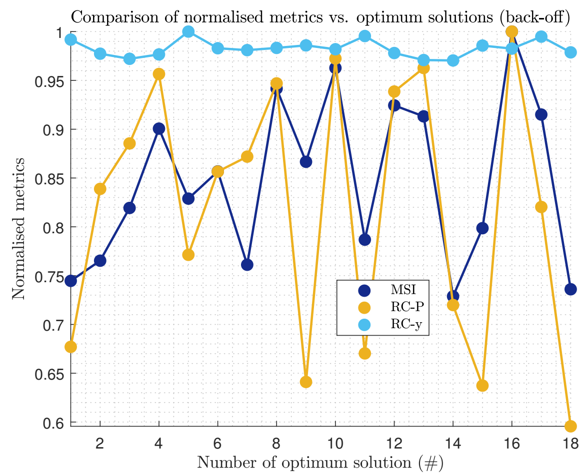
(a) Translational accelerations at back-on sitting conditions



(b) Rotational velocities at back-on sitting conditions



(c) Translational accelerations at back-off sitting conditions



(d) Rotational velocities at back-off sitting conditions

Fig. 7: The comparison of the optimum solutions for driving on the road class B profile (Figure 2) with regards to various metrics (RCZ, RCX, RCY, RCP, RCy and MSI) at both back-on and back-off sitting conditions.

function for optimising the suspension systems with regards to motion sickness mitigation. However, the root mean square of the pitch velocities seems more suitable, and should be considered either on its own or in combination with the root mean square of the weighted vertical accelerations.

Further work is in progress to investigate the above conclusions with different road profiles and by conducting different optimisation scenarios to compare the suitability of different cost functions with regards to motion sickness mitigation. The validation of these outputs through experimental studies and the subjective evaluation of motion sickness is under consideration.

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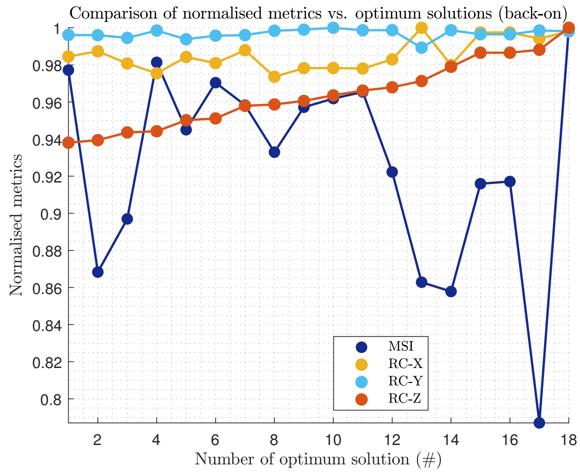
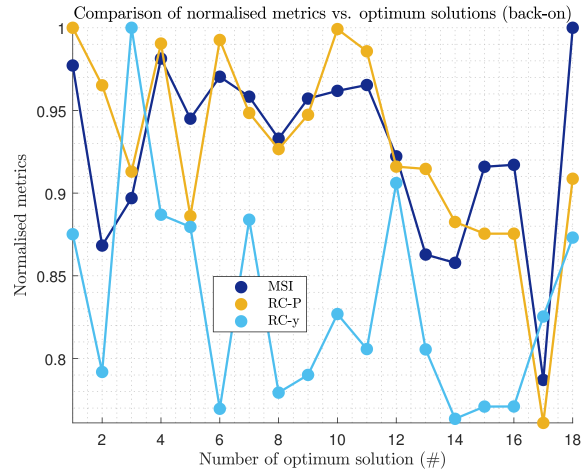
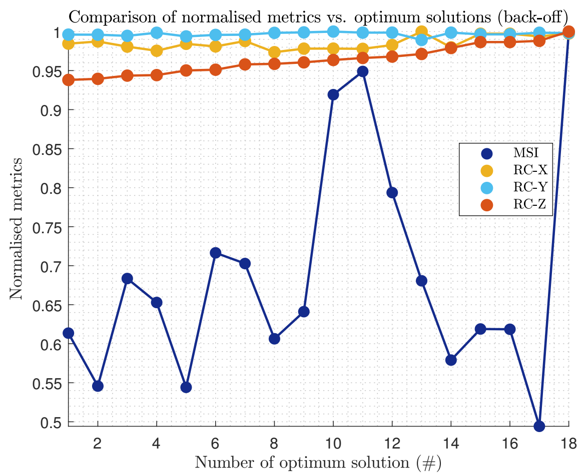


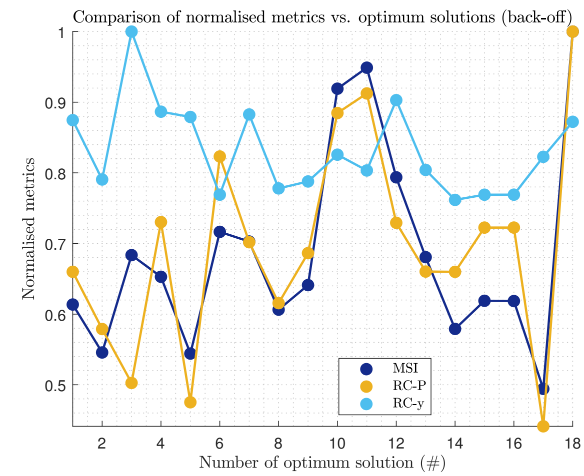
(a) Translational accelerations at back-on sitting conditions



(b) Rotational velocities at back-on sitting conditions



(c) Translational accelerations at back-off sitting conditions



(d) Rotational velocities at back-off sitting conditions

Fig. 8: The comparison of the optimum solutions for driving on the road class C profile (Figure 2) with regards to various metrics (RCZ, RCX, RCY, RCP, RCy and MSI) at both back-on and back-off sitting conditions.

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